Principles of Reactor Safety

Nuclear Safety Principles and Engineered Safety Systems

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Focus of Nuclear Reactor Safety

Ensuring the integrity of the nuclear reactor fuel and of the radioactive fission product retention barriers is the focus of nuclear reactor safety.

Nuclear Reactor Safety

- Basic purpose of nuclear reactor safety is to
  maintain integrity of multiple barriers to fission product release
- Accomplished by three-level *defense-in-depth* approach
- Control strategies developed to aid steady-power operations and to limit severity and/or mitigate consequences of potential operational upsets

Defense-in-Depth Level 1

Prevention – seeks to avoid completely those operational occurrences that could result in system damage, loss of fuel performance, and abnormal releases of radioactivity; prevention measures include

- inherently stable operating characteristics to enable adequate reactor reactivity control and heat removal
- quality assurance program that assures material quality for structures/systems/components with adequate safety margins
- periodic testing and inspections to maintain operating performance of components/systems
- adequate operational instrumentation and automatic controls
- plant personnel training
- plant safety assessment identifying safety issues having potential to cause plant damage that may lead to unregulated radiation releases

Nuclear Power Plant Operational Safety Objectives

- Reactor core reactivity control
- Reactor core heat removal capability
- Fission product containment

Operational safety objectives accomplished by systems that control neutron population in reactor core and systems that keep reactor core covered with cooling water to remove heat from reactor fuel elements, thereby maintaining integrity of first and second fission product retention barriers

Light Water Reactor (LWR) Operational Reactivity Control

Reactor Neutron Population

Neutron Balance Equation

Rate of neutron population increase = Rate of neutron production – Rate of neutron absorption – Rate of neutron leakage

or Accumulation = Production – Losses

Neutron Multiplication Factor

$$k = \frac{\text{neutron production}}{\text{neutron losses}}$$

Reactivity Defined

- Concept used to “quantify” system’s neutron multiplication behavior; like neutron multiplication factor, cannot be measured directly
- Nuclear system is “critical” when neutron production and loss rates are equal (k = 1)
- k – 1 represents “excess multiplication” of system’s neutron population
- (k – 1)/k represents system “fractional excess multiplication,” or system “reactivity” (ρ)

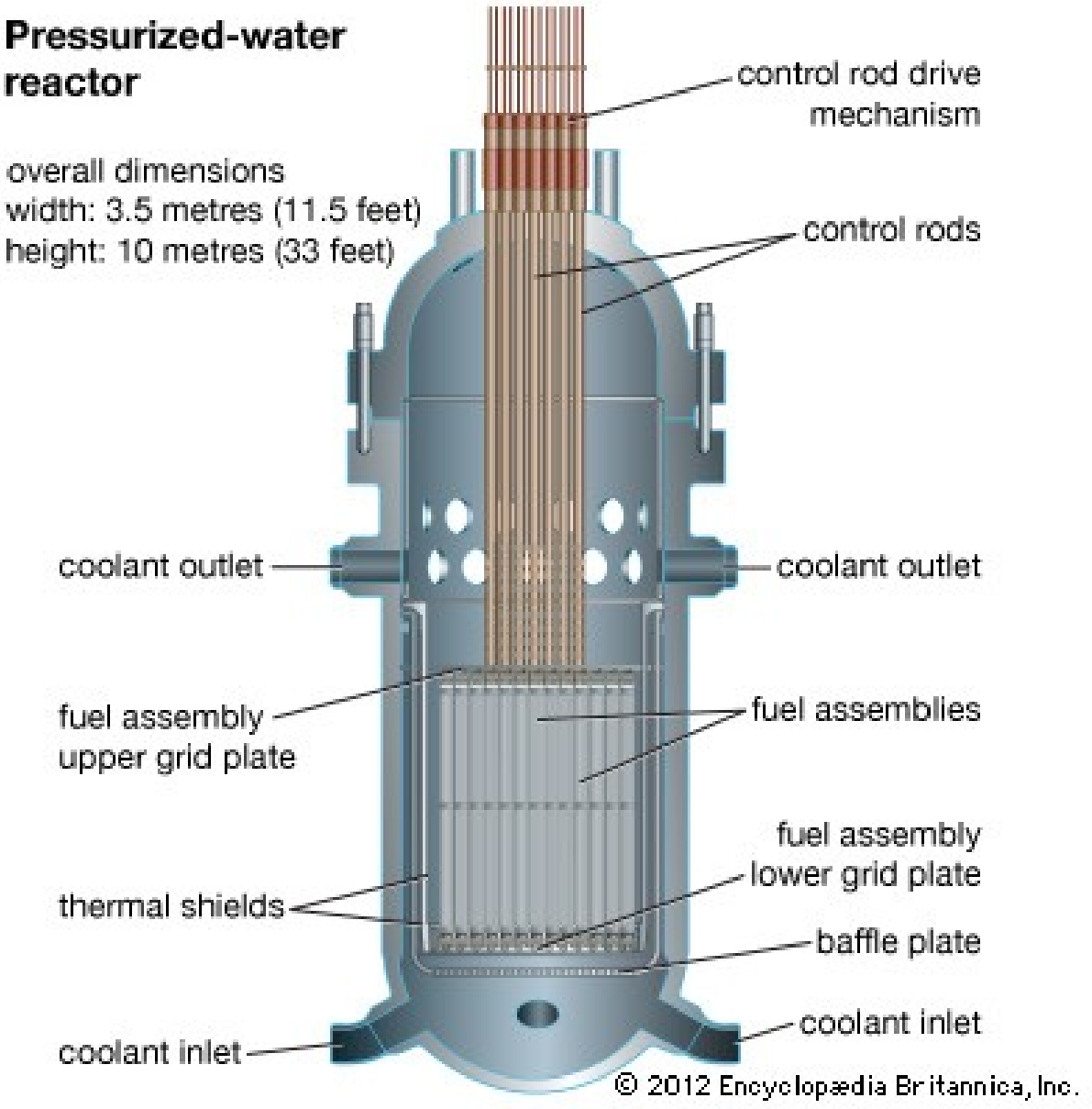
Nuclear Reactor Reactivity

Reactor has sufficient nuclear fuel to operate continuously for 18-24 months

- Reactor core fuel loading consists of supercritical mass of U-235 (excess reactivity)
- Core reactivity controls limit neutron population available to produce U-235 fission so that reactor just critical ($k = 1$)
- Reactivity controls adjusted during core operating life to keep reactor critical ($k = 1$) as U-235 burned up

Pressurized Water Reactor (PWR) Reactivity Control Systems

- Short-term
  - Control rods (within fuel assemblies)
    - Drive mechanisms on top of reactor vessel
    - Provide routine power control
    - Contain neutron absorbing material, generally boron carbide (B_4C)
- Intermediate/Long-term
  - Soluble neutron absorber (boric acid) in reactor coolant
    minimizes control rod use over core life


Pressurized-water reactor
overall dimensions
width: 3.5 metres (11.5 feet)
height: 10 metres (33 feet)
control rod drive mechanism
control rods
coolant outlet
coolant outlet
fuel assembly upper grid plate
fuel assemblies
fuel assembly lower grid plate
thermal shields
baffle plate
coolant inlet
coolant inlet
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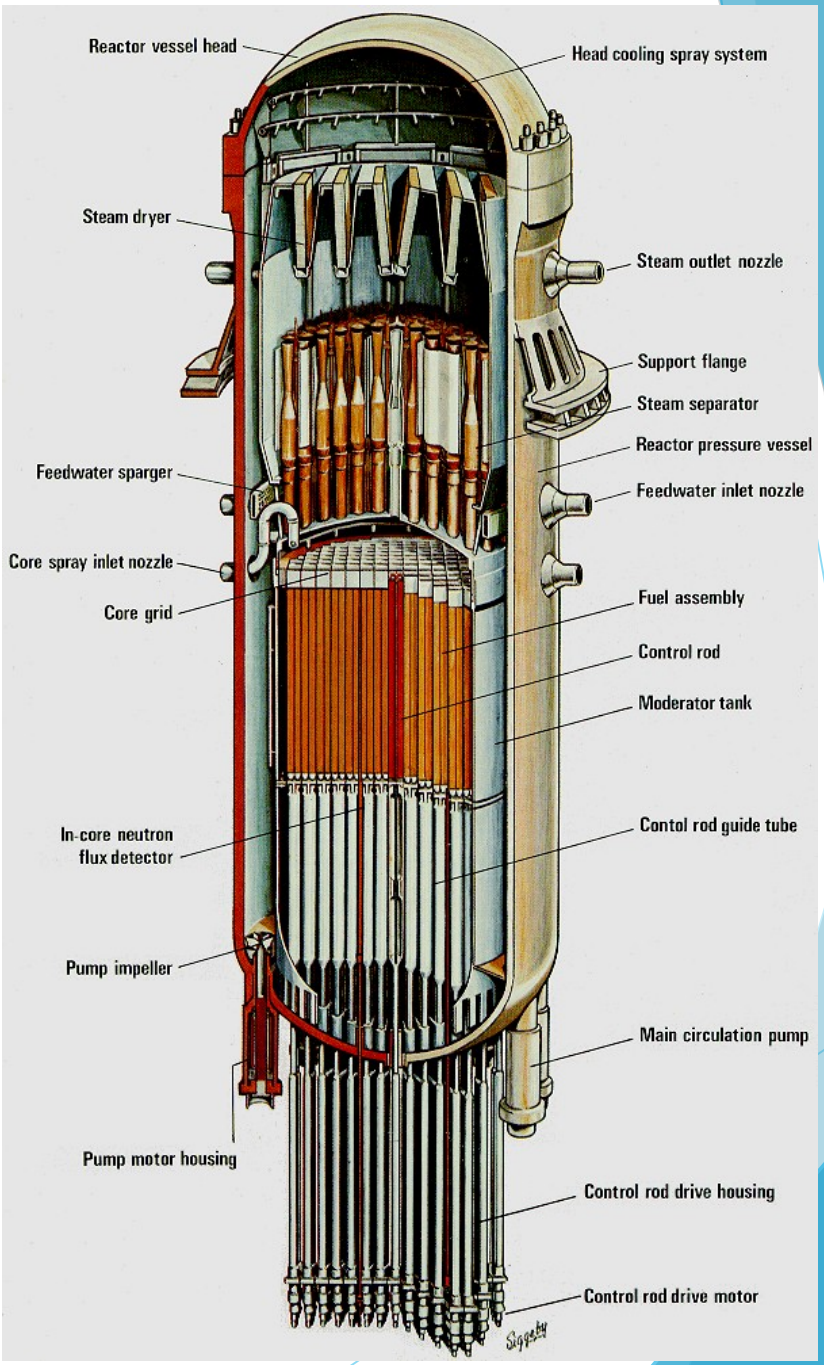
Boiling Water Reactor (BWR) Reactivity Control Systems

- Short-term
  - Control rod motion (regulating rods)
  - Reactor coolant flow rate adjustment
    - Negative reactor coolant/moderator void feedback
    - Power varies directly with coolant flow rate
- Long-term/Large Change Control
  - Control rod motion (shim rods)
    - Drive mechanisms on bottom of reactor vessel (avoids moisture separators and steam dryers at top of vessel)
    - Contain B_4C material

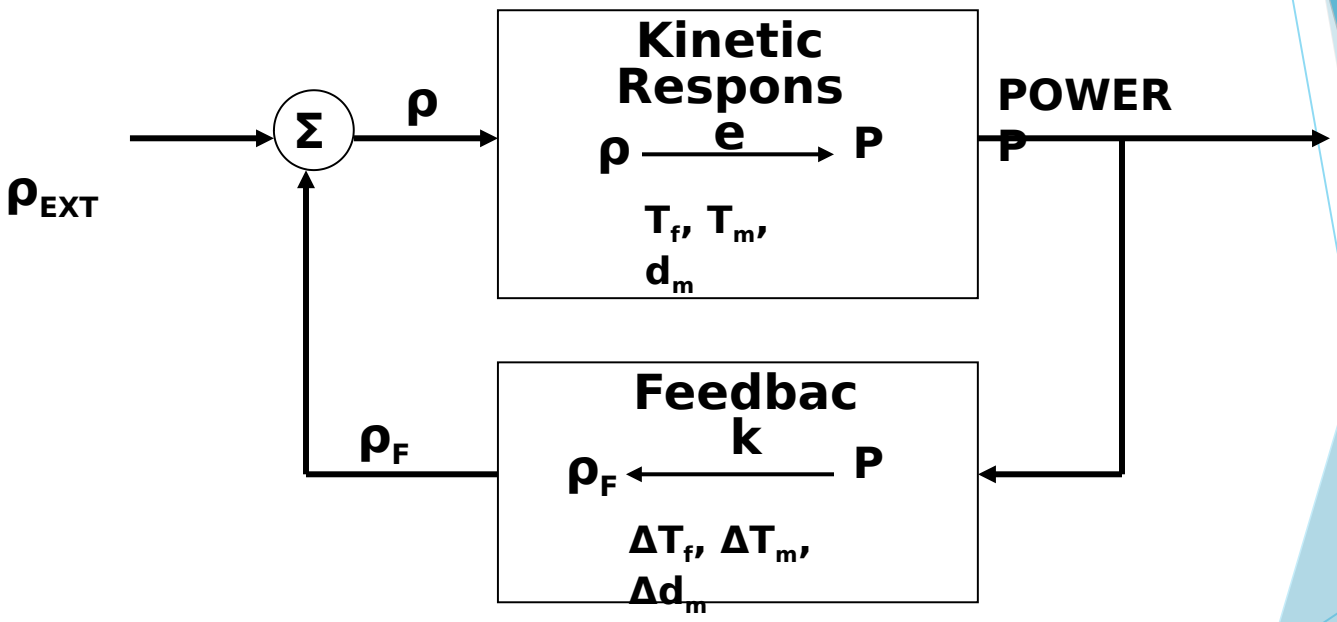
Boiling Water Reactor



Reactivity Feedback Mechanisms

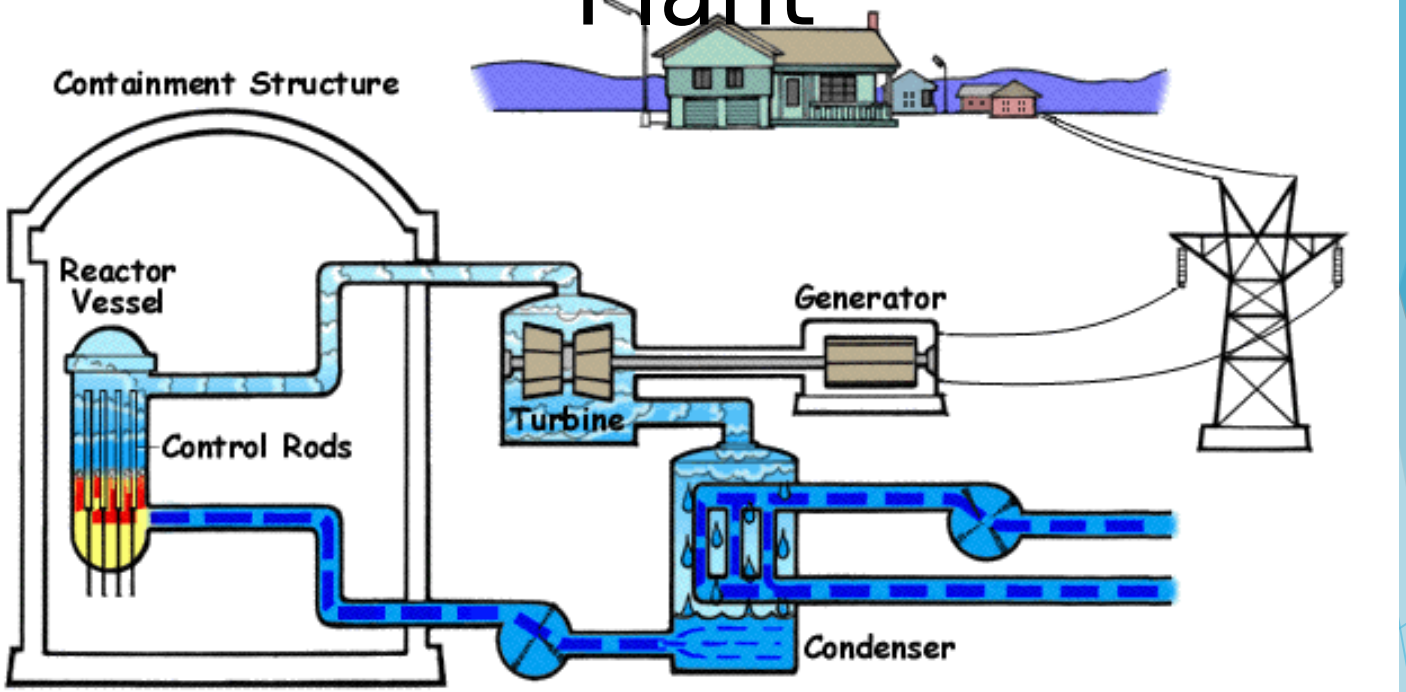
- Reactor core reactivity change causes change in neutron population, causing change in reactor heat generation
  - Reactor design features limit magnitude of core reactivity changes
- Change in heat generation produces changes in reactor operational parameters that oppose initial reactivity change (automatic feedback mechanisms)
  - Mechanisms independent of operator action, operate on short time scales, and very important to reactor operation and safety
- Feedback mechanisms described as reactivity coefficients
  - Rate of change of core reactivity with respect to change in feedback variable (e.g., fuel temperature, moderator temperature, moderator voids)

Automatic Reactivity Control

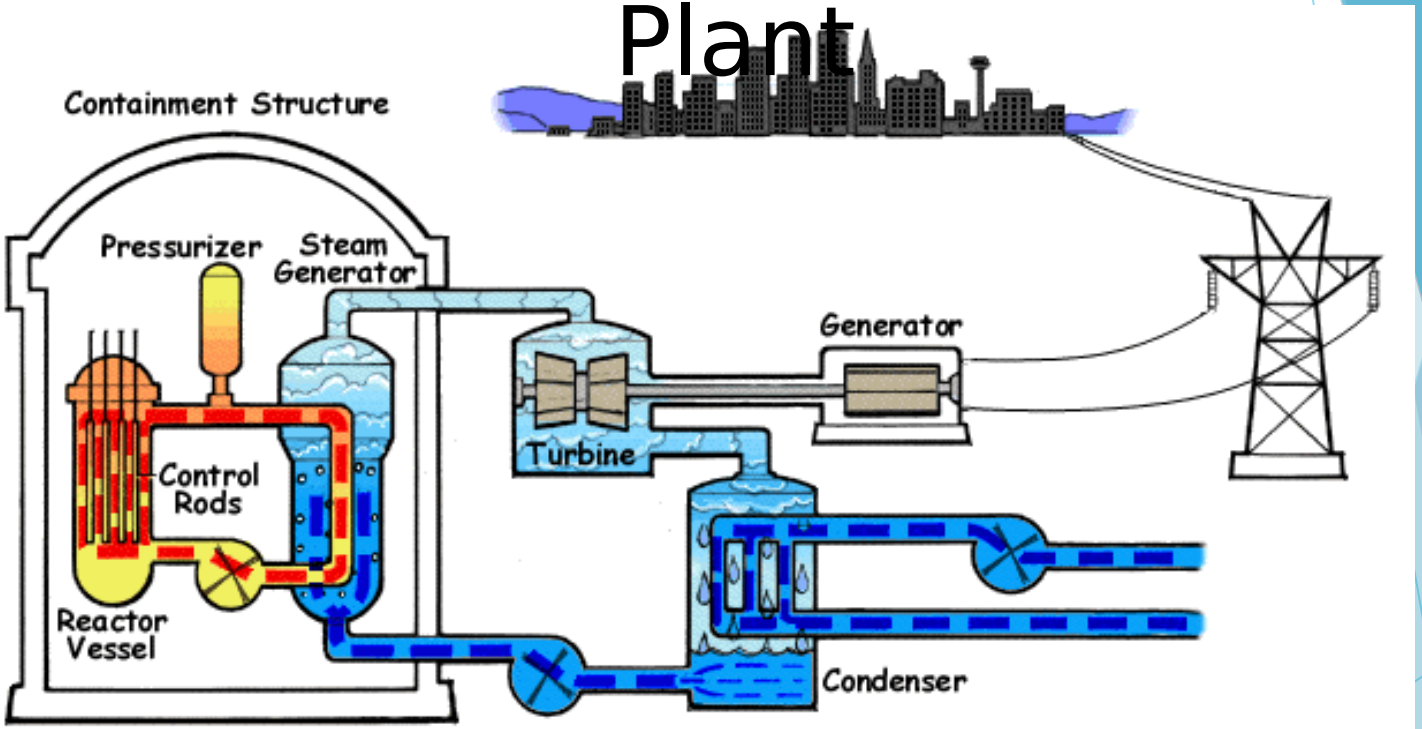


LWR Operational Heat Removal

Boiling Water Reactor Power Plant



Pressurized Water Reactor Power Plant



LWR Shutdown Heat Removal

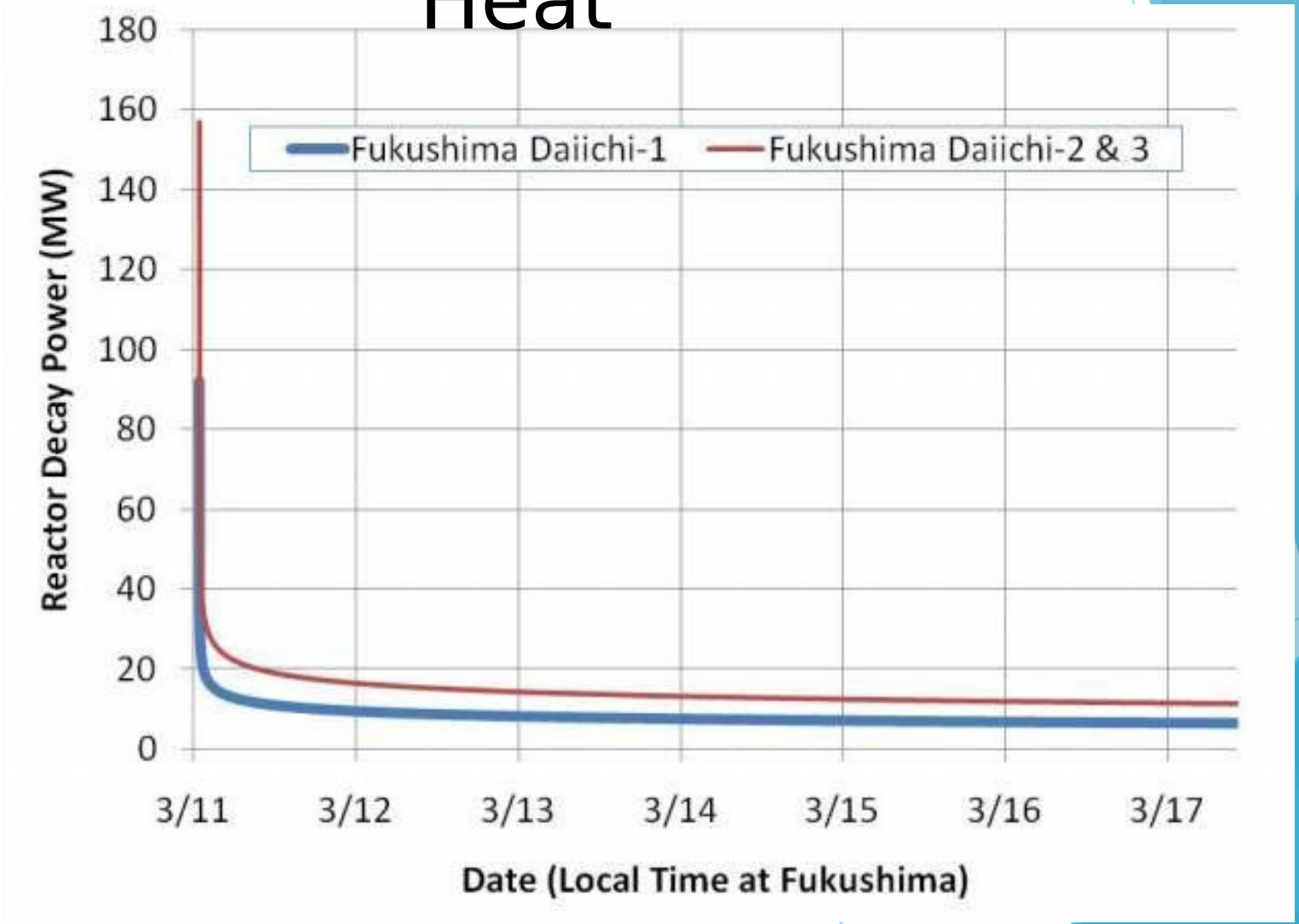
(also called Residual Heat Removal or Decay Heat Removal)

Nuclear Fission Energy Disposition

	Mev	%
Fission Fragment Kinetic Energy	168	84
Fission Neutron Kinetic Energy	5	2.5
Prompt Gamma Ray Energy	7	3.5
Fission Fragment Delayed Radiation		
Beta Particles	8	4
Gamma Rays	7	3.5
Radiative Capture Gammas	5	2.5
Total	200	100

Delayed radiation from fission fragment radioactive decay accounts for ≈7.5% of total fission energy and continues to generate heat in reactor core even after fission process is terminated

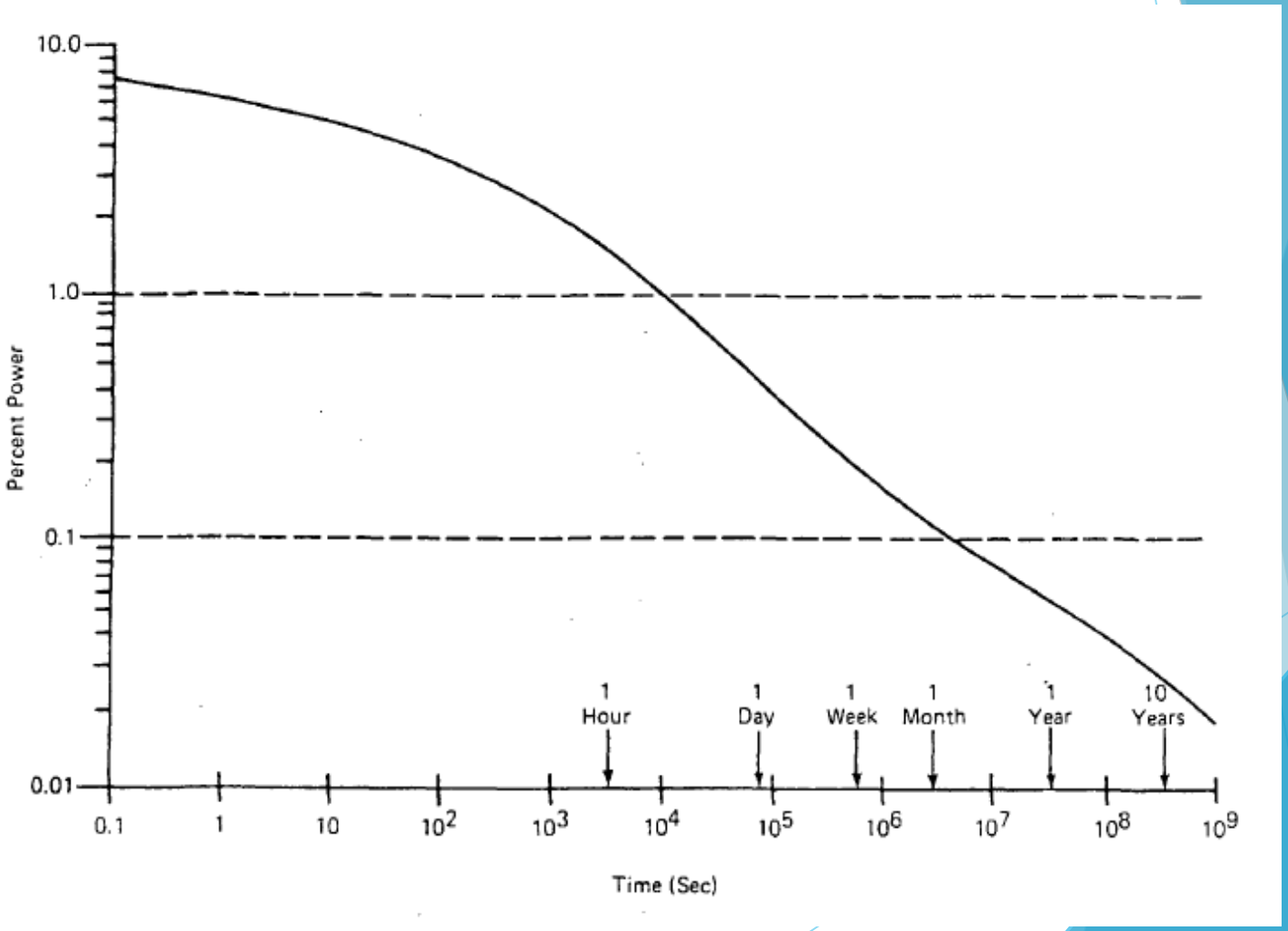
Decay Heat


180
160
140
120
100
80
60
40
20
0
Reactor Decay Power (MW)
Fukushima Daiichi-1
Fukushima Daiichi-2 & 3
3/11
3/12
3/13
3/14
3/15
3/16
3/17
Date (Local Time at Fukushima)

Reactor Decay Heat Generation

- Long half-life radioisotopes continue to generate heat within nuclear fuel for hundreds of thousands to millions of years, but at very slow rate due to slow radioactive decay
- High radioactivity associated with relatively short half-life radioisotopes generates most of decay heat
- While decay heat generation drops off quickly as shorter half-life radioisotopes disappear, one week after reactor shutdown decay heat power still ≈1.5% of reactor operating power
  - Used nuclear fuel decay heat must be removed in tank of circulating water for few years until generated heat sufficiently reduced such that air cooling adequate to keep fuel rods from overheating

Decay Heat Production Following Reactor Shutdown (WASH-1400)

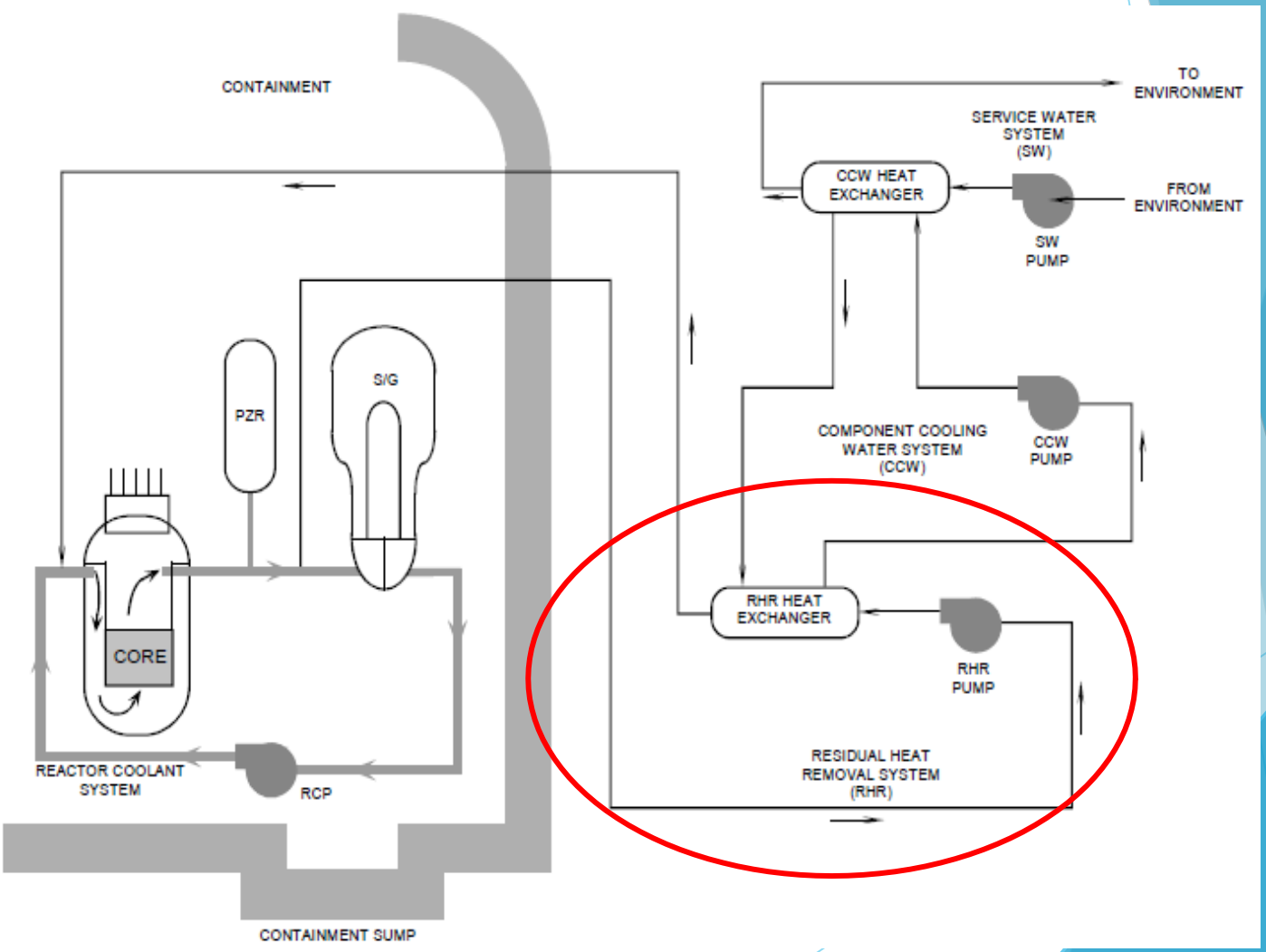


LWR Residual Heat Removal System

System consists of redundant RHR pumps, RHR heat exchangers, and isolation valves

- System located outside of reactor containment building
- Piping penetrates containment building and connects to reactor coolant system
- Heat exchangers connected to plant component cooling water system

Example PWR RHR System

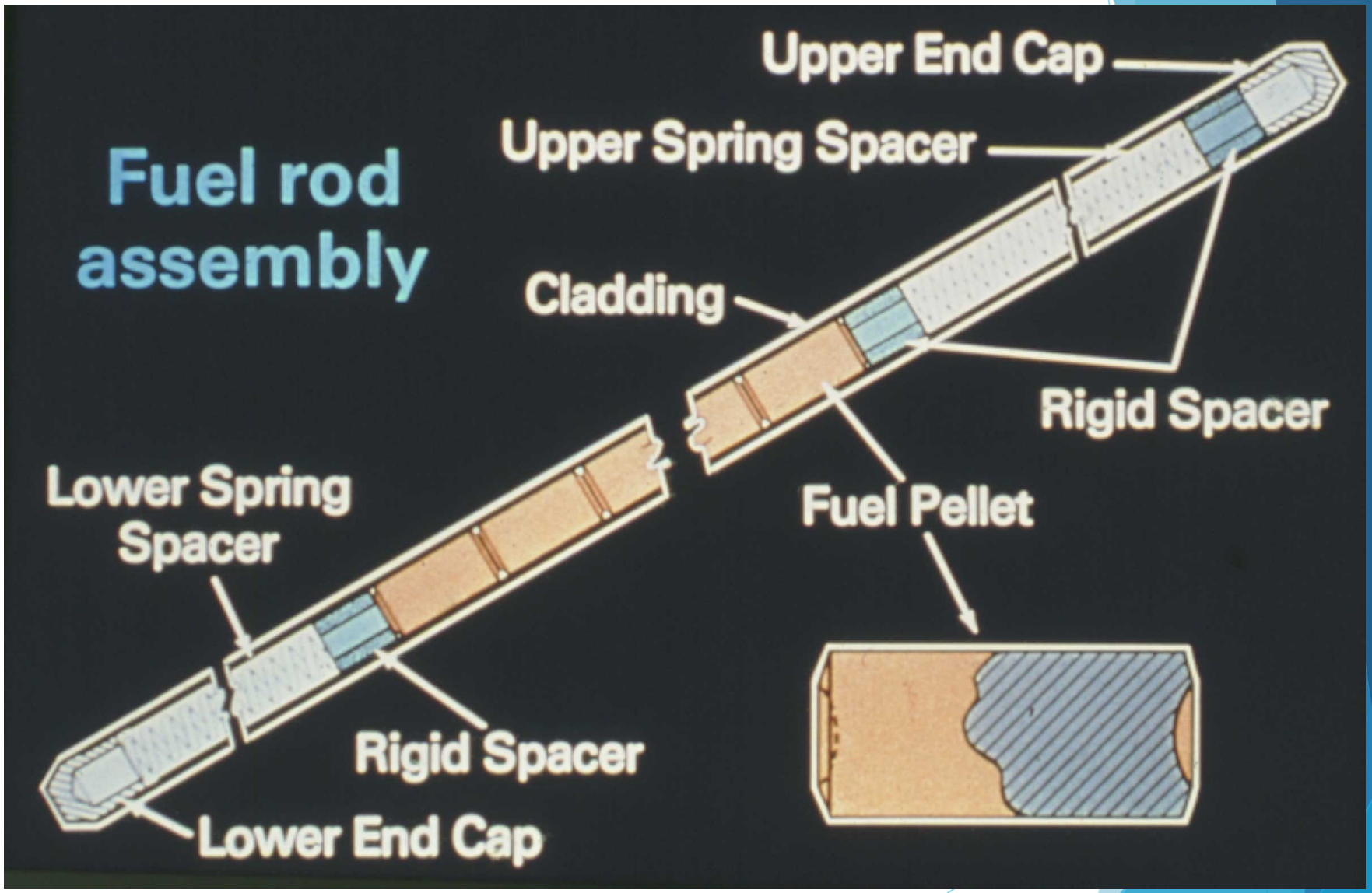


LWR Fission Product Containment

Fission Product Retention Barriers

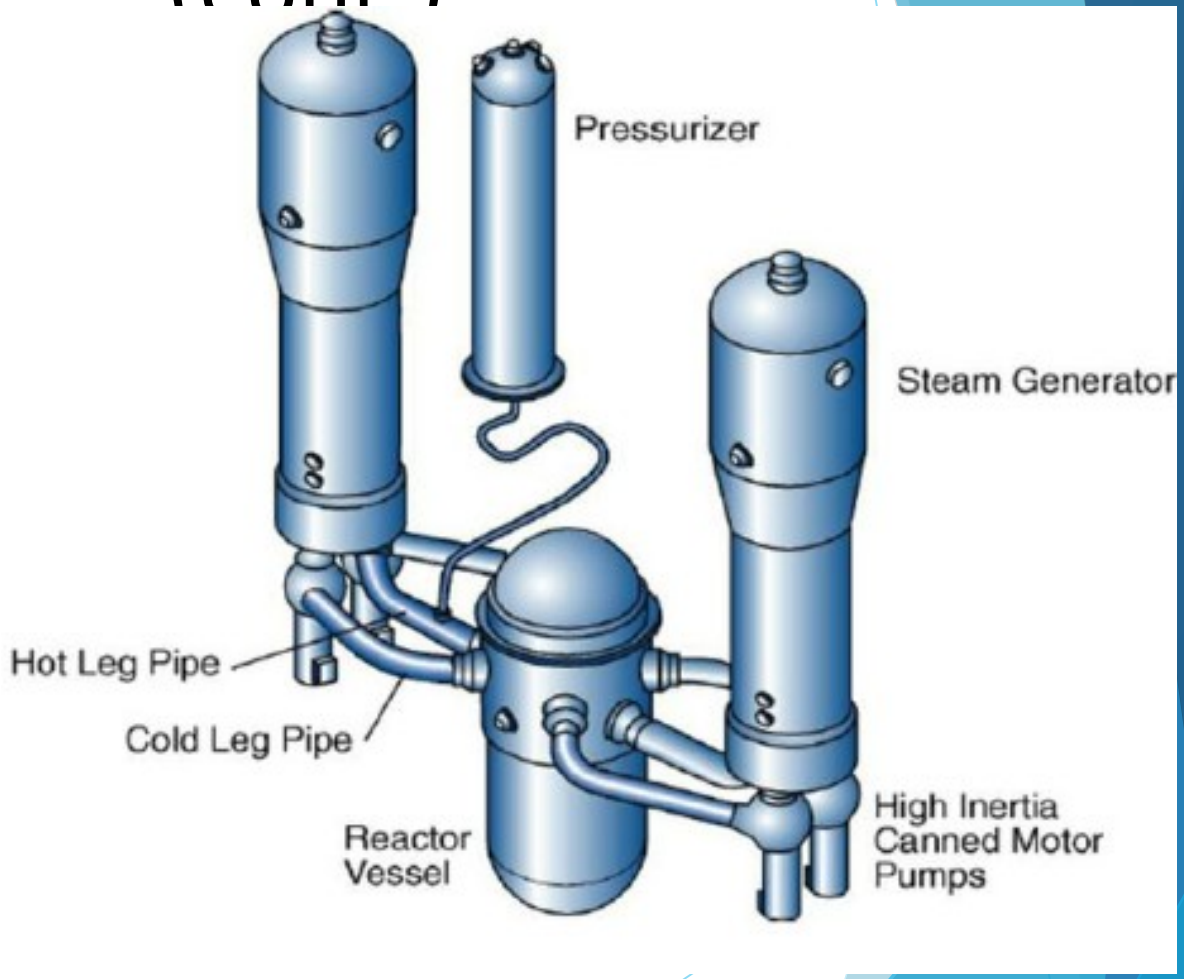
Defense-in-depth barriers

- Fuel pellet
- Fuel rod cladding
- Reactor coolant system boundary (all reactor coolant system structures and components)
- Reactor containment building

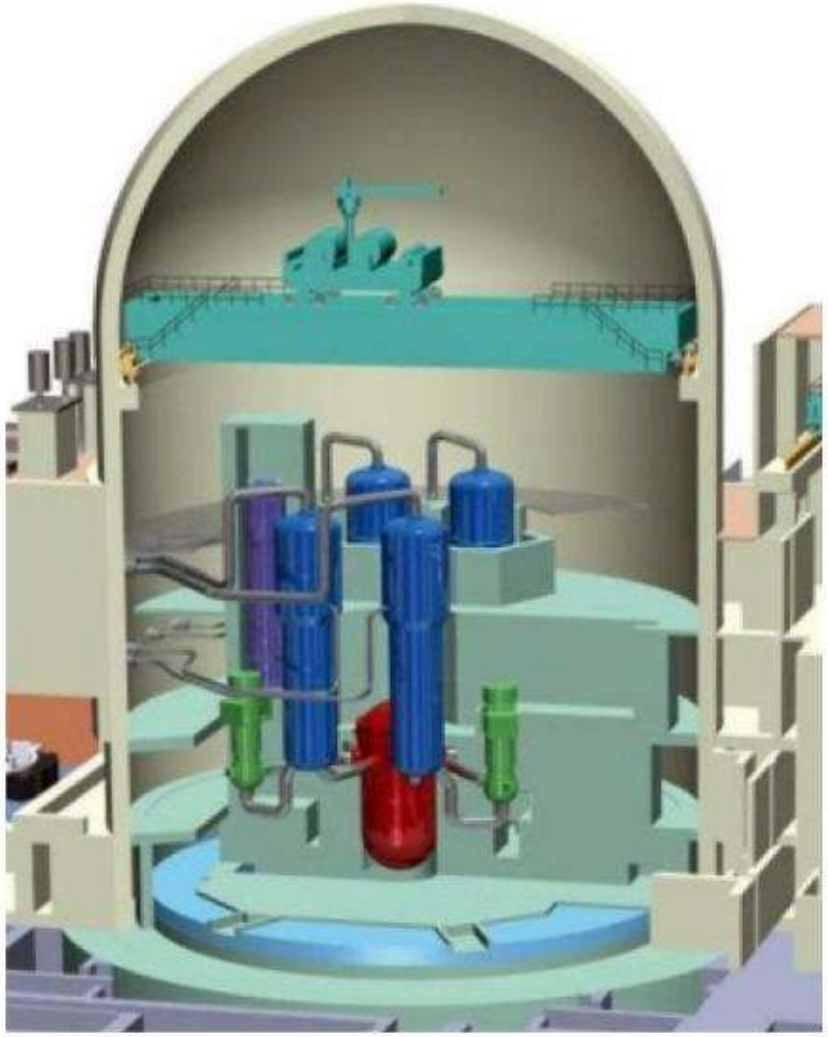

Fuel rod assembly
Upper End Cap
Upper Spring Spacer
Cladding
Rigid Spacer
Fuel Pellet
Lower Spring Spacer
Rigid Spacer
Lower End Cap

Fission Product Retention Barriers (cont.)

Reactor Coolant System Boundary – in event of fuel rod damage, fission products confined within piping and vessels of reactor cooling system



Fission Product Retention Barriers (cont.)



*Source: NRC

PWR Reactor Containment Building – low-leak-rate, steel-reinforced concrete structure provides barrier to atmospheric release of radionuclides from nuclear fuel damage

Defense-in-Depth Level 2

Protection – seeks to halt or deal with unlikely, low-probability incidents and operational occurrences that cause reactor shutdown and could lead to minor fuel damage and small releases of radioactivity; protection measures include

- fast reactor shutdown (reactor trip)
- primary coolant system over-pressure relief
- system and component operational safety interlocks
- automatic monitoring and safety system initiation
- Transient (off-normal) operating guidelines and procedures
- measurement and control of radiation levels, doses, and radioactivity releases

Defense-in-Depth Level 3

Mitigation – seeks to limit the consequences of potential accidents that might occur despite prevention and protection measures; mitigation measures include

- emergency feedwater system for reactor heat removal
- emergency core cooling systems for reactor cooling water replenishment and heat removal
- emergency electrical power (diesel generators, station batteries, and inverters)
- radioactivity containment structures
- emergency plan to assure availability of accident response resources so health and safety of public not compromised

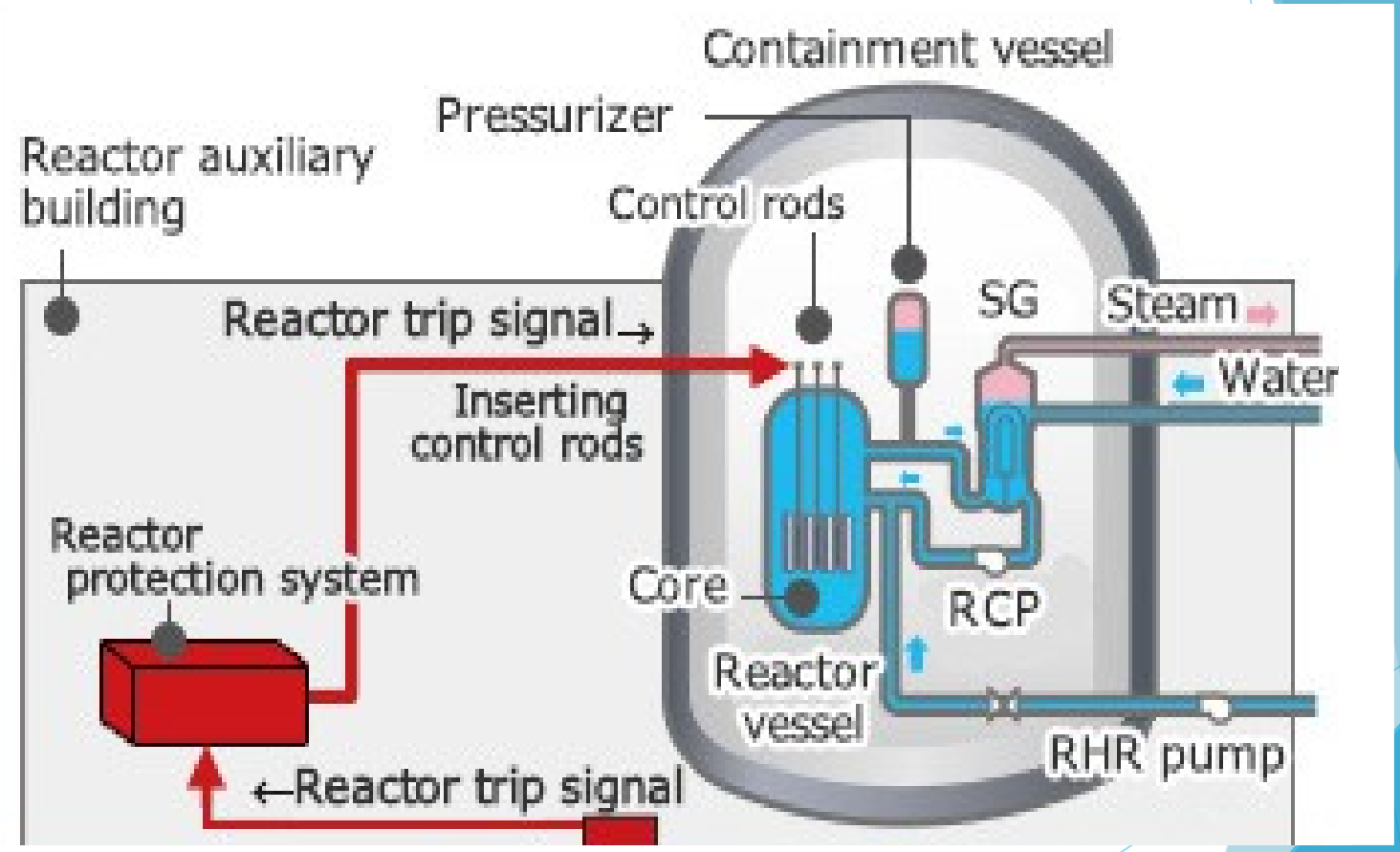
Nuclear Power Plant Operational Transient/Accident Safety Objectives

- Reactor core reactivity control
- Reactor coolant inventory control
- Reactor core heat removal capability
- Reactor containment building heat removal capability
- Fission product containment

Engineered Safety Features and Functions

- Reactor Protection System (RPS) – reactor trip terminates nuclear chain reaction (core reactivity control)
- Emergency Core Cooling Systems (ECCS) – injects coolant into reactor vessel upon loss of reactor coolant inventory and removes heat from nuclear fuel (reactor coolant inventory control & core heat removal capability)
- Post-Accident Heat Removal (PAHR) – removes heat from containment building to prevent over-pressurization (containment heat removal capability)

Reactor Protection System



Example RPS Trip Signals

- High neutron flux
- High reactor power
- High reactor coolant system temperature
- High reactor coolant system pressure
- Low reactor coolant flow
- Low feedwater flow
- Steam turbine trip

Emergency Core Cooling Systems

- High pressure coolant injection systems
  - automatically actuated upon rapid reduction in reactor coolant system pressure
  - redundant pumps and valves
  - makeup water reservoir
- Low pressure coolant injection systems
  - automatically actuated when reactor coolant system depressurized
  - redundant pumps and valves
  - removes heat from and recirculates recovered coolant and makeup water

Engineered Safety Features and Functions (cont.)

- Reactor Containment Building Integrity (CI) – prevents release of post-accident radioactivity (fission product containment)
- Post-Accident Radionuclide Removal (PARR) – removes radionuclides from containment atmosphere and filters containment effluents (fission product containment)

Engineered Safety System Reliability

Reliability design principles and criteria assure protection and safety function availability at all times

- System/component *redundancy* provides single-failure protection
- System/component *diversity* provides common-mode failure protection
- *Physical separation* of equipment provides protection against simultaneous loss (e.g., by fire or flood)

Fail-Safe Design Principle

Assures that systems and components designed to automatically return to safest condition upon failure or loss of power so as not to complicate operational upset condition

Gen 2 vs. Gen 3+ Reactor Safety

- Generation 2 reactor plant safety has inherent weakness – safety devices added to reactor plant design as result of accident considerations
  - safety dependent on *active* Defense-in-Depth Level 3 mitigation measures (e.g., AC and DC powered equipment) and early reactor operator intervention for operational upset condition
- Safety of Generation 3+ reactors is fundamental consideration of reactor plant design
  - *passive* safety makes use of gravity, natural circulation, high temperature resistance
  - no operator intervention required to mitigate operational upset/accident conditions

Small Modular Reactor and Microreactor Safety

SMR/Microreactor Defense-in-Depth

- Main goal of designs to eliminate accident initiators and prevent accident consequences
- For some designs, implementation of defense-in-depth concept is passive function, rather than active function
- Current lack of practical guidance for assessing implementation of defense-in-depth concept likely to delay licensing process

SMR/Microreactor Operational Safety Objectives

- Operational safety objectives same as large reactors
  - Reactor reactivity control
  - Reactor heat removal capability
  - Fission product containment
- Implementation of operational safety objectives varies with reactor design
  - Variety of active and passive approaches for reactor shutdown systems
  - Variety of passive heat removal systems/mechanisms
  - For some designs, reactor core melt with potential for radioactivity release may not be possible

SMR/Microreactor Safety Features

Certain common characteristics of smaller reactors lend themselves to inherent and passive safety features

- Smaller core sizes enable integral pool-type reactor coolant system designs
- Lower core power densities facilitate operational passive heat removal by natural convection of single-phase coolant or heat transfer by conduction and radiation
- Smaller radionuclide inventories and larger core surface-to-volume ratios facilitate decay heat removal by redundant passive systems/mechanisms

SMR/Microreactor Positive Safety Attributes

- Reduced number of systems and components results in simplicity of plant design, operation, and maintenance
- Increased reactor self-regulation under accident conditions and higher margin to fuel failure results in simpler plant operation and maintenance
  - Some designs require no operator intervention to mitigate potential accidents
- Designs generally incorporate containment structure as ultimate barrier to prevent radioactivity release
  - Some designs embed reactor system and containment structure below ground

SMR/Microreactor Safety Concerns

- Concerns related to passive safety systems
  - Reliability of passive safety systems not understood as well as active safety systems
  - Potential for undesired interaction between active and passive safety systems
  - Implications of incorporation of passive safety features and systems into advanced reactor designs to achieve targeted safety goals may not yet be fully understood
  - Potential aging of passive safety systems/components over plant life (e.g., corrosion, deposits on heat exchanger surfaces, etc.)

SMR/Microreactor Safety Concerns (cont.)

- Additional safety concerns
  - Multiple reactors on single site may increase susceptibility to common cause failures
  - Compactness of some SMRs may involve sharing or multipurpose use of safety-related systems, potentially compromising safety system independence
  - Type, extent, and implementation of measures to address all levels of defense-in-depth may differ significantly considering large variability of SMR types